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A bubble dynamics-based model for wall heat flux partitioning during nucleate flow boiling

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ABSTRACT

Many physical mechanisms are responsible for wall heat transfer during nucleate flow boiling, such as evaporation of microlayers, gradual rewetting, transient conduction, and forced convection. The nature of these mechanisms tightly connects with the complex dynamics of nucleating bubbles (e.g., growth, sliding, and merger), leading to considerable challenges of modeling the partitioning of wall heat flux into these mechanisms. In this study, we proposed a mechanistic model for wall heat flux partitioning relying on the coupling of heat transfer mechanisms with relevant bubble dynamics. The heat transfer via evaporation of superheated liquid (including microlayers) and gradual quenching over dry spots during the bubble growth period was determined as the latent heat transported to growing bubbles using bubble energy balance and growth equations. The heat transfer over the areas swept by bubbles while sliding and merger whose thermal effect is counted from after the bubble departure to the instant it changes to forced convection or nucleation was quantified by the conventional transient conduction combining with the bubble growth equation and wall functions. The residual wall heat transfer corresponds to forced convection over the region unoccupied by bubbles and the region it replaces transient conduction during the remaining period of bubbling cycle. These three primary mechanisms mechanistically constitute the present wall heat flux partitioning model that is physically concrete and confirmed to has good predictability against experimental data for nucleate boiling at a variety of flow conditions.

1. Introduction

Nucleate boiling with a particularly high rate of heat transfer has been desired for many industrial applications, such as power generation and cooling of heated mediums (e.g., rocket engines and electronic devices). Nevertheless, to benefit from nucleate boiling, the heat transfer from a heated wall to coolant must be optimized to avoid the occurrence of surface burnout, which causes the loss of integrity of heating elements and threatens the safety of related systems. For this demand, it is essential to develop analysis tools for predicting the heat transfer process.

So far, various theoretical models and correlations have been proposed for wall boiling heat transfer. The models and correlations can be classified into two main groups. One group includes empirical correlations for local heat transfer coefficient like what reported by Chen [1] and Shah [2]. The other group includes mechanistic models or semi-empirical correlations describing the partitioning of wall heat flux into physical mechanisms responsible for wall boiling heat transfer [3].

Among these kinds of models and correlations, the mechanistic one of heat flux partitioning has been receiving many interests from recent studies on nucleate flow boiling. As its name, a model of this kind can predict not only the local heat transfer rate as empirical correlations of the first group, but also the partitioning of wall heat flux into evaporation, quenching, convection, and so on. The partitioning is particularly helpful for multidimensional analyses of boiling flows in which the vapor content and liquid temperature are tightly connected with partitioned heat fluxes. Additionally, it brings an opportunity to generalize wall boiling heat transfer with a model of this kind by getting right physical mechanisms involve. For these reasons, the present study paid attention to the mechanistic modeling of wall heat flux partitioning.

Despite a significant number of existing models, none of them obtains satisfactory quantification for heat transfer accompanying bubbling events. The enhancement of wall heat transfer during nucleate boiling has been attributed to the presence of vapor bubbles. However, it is very challenging to determine qualitatively and

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Nomenclature

A	fractional surface area
C_b	ratio of bubble diameters
c_p	specific heat
D	bubble diameter
f_b	bubbling frequency
h	heat transfer coefficient
h_{lv}	latent heat
Ja	Jakob number
K	influence area factor
k	thermal conductivity
l	sliding distance
N_a	active nucleation site density
Pr	Prandtl number
q	heat flux
R	reduction factor
s	distance between nucleation sites
t	time
u	velocity
y	fractional condensation area
V	volume

Greek symbols

ΔT	temperature gradient
α	void fraction
α_l	thermal diffusivity
ρ	density
μ	dynamic viscosity

Subscripts

b	bubble or subcooling
cd	condensation
fc	forced convection
g	growth
l	liquid
lat	latent
m	maximum, or measured
p	predicted
rel	relative
tc	transient conduction
v	vapor
w	wall, or waiting

quantitatively physical mechanisms responsible for this enhancement. It was doubtful that whether the evaporation of microlayers at the bubble base or transient conduction in the wake of departing bubbles dominates the wall heat transfer. Also, how significant the bubble sliding and merger that are typical in nucleate flow boiling affect the wall heat transfer. In the following sections of this paper, it will be indicated that the nature of heat transfer over the place where vapor bubbles anchor varies complexly throughout the bubbling cycle with the bubble dynamics. Then, a new mechanistic model will be developed for wall heat flux partitioning during nucleate flow boiling relying on the coupling of heat transfer mechanisms with related bubble dynamics.

2. Survey on modeling of heat transfer associated with vapor bubbles

There have been different viewpoints on the heat transfer accompanying bubbling events during nucleate boiling. Forster and Zuber [4], Tien [5], and Zuber [6] suggested that the high rate of wall boiling heat transfer was due mainly to the strong liquid agitation induced bubbles. The viscous shear between a rising vapor bubble and surrounding liquid creates a flow field that enhances heat transfer via a so-called micro-convection over the nucleation site. The micro-convection was used to represent the heat transfer over the entire heated wall (including nucleation sites), and it was expressed via either the bubble diameter at departure [4] or the density of active nucleation sites [5,6]. The cyclic nature of bubbling events, which would have a significant impact on wall heat transfer, was not included in these models.

Aside from the hydrodynamic interpretation, Han and Griffith [7] claimed that the repeated transport of a superheated liquid layer (or bulk convection) over nucleation sites could describe well the intensive heat transfer during nucleate boiling. Mikic and Rohsenow [8] also suggested transient conduction to the reformed thermal layer that is pumped away by departing bubbles (the first stage of bulk convection, not including microlayer evaporation) for the heat transfer enhancement. Both these models are principally the transport of sensible heat via pure conduction to the liquid layer–a semi-infinite medium next to the heated wall, and they were expressed via three primary nucleating parameters, including bubble departure diameter, nucleation site density, and bubbling frequency.

Though the pioneering theoretical models above are oversimplified, mostly emphasized on one central physical mechanism (i.e., micro-convection and transient conduction), they have paved the way for further modeling of wall heat flux partitioning during nucleate boiling in many later studies. In Table 1, a summary of some existing models is given with an emphasis on the manner used to formulate the heat transfer associated with nucleating bubbles.

It can be seen from this table that the early models applicable to nucleate boiling with isolated and stationary bubbles were comprised of heat transfer through microlayer evaporation, quenching or transient conduction over an influence domain that is constantly proportional to the bubble projected area, and natural or forced convection outside the bubble-influenced domain [6,7,9–12]. The evaporative heat flux was computed as the sensible heat conducted to microlayers or the latent heat transported to vapor bubbles. The information on microlayer thickness or bubble departure diameter is necessary for this calculation. The quenching heat flux was determined using the transient conduction equation given by Mikic and Rohsenow [8] or Del Valle and Kenning [10]. The influence area and period over which transient conduction is active are very diverse among the models, as indicated in Table 1. The differences resulted in strong arguments on the degree of significance of microlayer evaporation and bubble-induced quenching.

Owing to the debates on the characteristics of heat transfer mechanisms and following arguments, various experimental studies that directly measure the heat transfer associated with a single bubble using advanced techniques (e.g., infrared thermography and microheater arrays) have been motivated [13–17]. These studies figured out valuable features of heat transfer at nucleation sites. First, the evaporation of microlayers was shown to contribute less than about 25% of the total heat transfer and the equivalent bubble diameter was much smaller (about two times lesser) than the measured bubble diameter. This finding came to a conclusion that the growth of a bubble must be due primarily to the evaporation of surrounding superheated liquid, rather than due only to the microlayer evaporation.